A group-based binary splitting algorithm For UHF RFID anti-collision systems

Article (Accepted Version)

A Group-based Binary Splitting Algorithm For UHF RFID Anti-collision Systems

Jian Su, *Member, IEEE*, Zhengguo Sheng, *Senior Member, IEEE*, Alex. X. Liu, *Fellow, IEEE*, Yu Han, and Yongrui Chen, *Member, IEEE*

***Abstract*—Identification efficiency is a key performance metrics to evaluate the ultra high frequency (UHF) based radio frequency identification (RFID) systems. In order to solve the tag collision problem and improve the identification rate in large scale networks, we propose a collision arbitration strategy termed as group-based binary splitting algorithm (GBSA), which is an integration of an efficient tag cardinality estimation method, an optimal grouping strategy and a modified binary splitting. In G-BSA, tags are properly divided into multiple subsets according to the tag cardinality estimation and the optimal grouping strategy. In case that multiple tags fall into a same time slot and form a subset, the modified binary splitting strategy will be applied while the rest tags are waiting in the queue and will be identified in the following slots. To evaluate its performance, we first derive the closed-form expression of system throughput for GBSA. Through the theoretical analysis, the optimal grouping factor is further determined. Extensive simulation results supplemented by prototyping tests indicate that the system throughput of our proposed algorithm can reach as much as 0.4835, outperforming the existing anti-collision algorithms for UHF RFID systems.**

***Index Terms*—RFID, anti-collision, sub-frame, modified binary splitting, grouping factor.**

I. Introduction

RADIO frequency identification (RFID) technology is widely used in modern industrial fields, such as traceability management [1], supply chains [2] and indoor robot navigation because of its key features such as feasibility, convenience and contactless nature. For the sake of reducing cost and making reader-to-tags communications worldwide available and compatible, many RFID standards are developed, including ISO 14443, ISO-18000-7, ISO 18000-6B, and EPC C1 Gen2 [3-4]. Among those standards, EPC C1 Gen2 is used for passive UHF RFID infrastructure and defines physical and logical requirements for a passive-backscatter and medium access control (MAC) settings to support reader-to-tags communications. Tags in a UHF RFID system are passive, which means that all of their operating energy are collected from the reader's RF waveform. It is necessary that the reader can provide enough power to energize tags and allow them to respond with valid messages. With reducing cost, passive tags become popular for large scale deployments. However, the emerging multiple tag collision problem happens when multiple tags communicate with a reader simultaneously using a common channel. Specifically, the collision problem in the UHF RFID system becomes more significant due to its primary applications in dense networks. Hence, the reader needs to adopt an efficient approach to achieve fast identification in UHF RFID systems.

To tackle the aforementioned collision problem, a number of anti-collision or tag identification solutions have been presented, which can be mainly categorized into Aloha-based [5, 6, 7, 8, 9, 10, 11], tree-based [12, 13, 14, 15, 16, 17, 18, 19, 20, 21] and hybrid algorithms [22, 23, 24, 25]. Tree-based algorithms include two types, namely query tree (QT) [12, 13, 15] based schemes and binary splitting (BS) [16, 17, 18, 19] schemes. The BS protocols are originally proposed for random access systems [18, 19]. The principle of the BS protocol is recursively dividing contending tags into smaller groups until each group contains up to one tag. The fastest tree-based anti-collision methods have been presented to solve collision among messages with Poisson arrivals and can achieve throughput of 0.487 [26]. However, such algorithms have poor performance with non-Poisson arrivals such as batch arrival [19]. Tree-based algorithms are able to identify all tags especially for large number of tags. The difference between QT and BS is that, in QT-based methods, the collided tags are separated based on their unique identifiers (IDs), whereas in BS methods, the collided tags are split on the basis of random numbers generated by the tags. In the QT-based algorithm, each tag owns a prefix match circuit. The reader initializes an identification cycle by broadcasting a probe command, tags with a matching will respond to the reader. Intrinsically, the QT-based algorithm is based on a bit identification and tracking technology [26]. However, as the number of tags increases, it is unable to detect the position of collision efficiently due to the wide deviation of backscatter link frequency among tags [4][27, 28]. Therefore, the algorithms embedded in the bit identification and tracking technology are difficult to implement in UHF RFID systems [4, 14, 28-31].

Aloha-based algorithms commonly employ a frame structure which contains a certain number of time intervals (called

Corresponding authors: Yongrui Chen; Zhengguo Sheng

J. Su is with the School of Computer and Software, Nanjing University of Information Science and Technology, Jiangsu 210044, China (e-mail: sj890718@gmail.com).

Z. Sheng is with the Department of Engineering and Design, University of Sussex, Brighton BN1 9RH, U.K. (e-mail: z.sheng@sussex.ac.uk).

A. X. Liu is with the Department of Computer Science and Engineering, Michigan State University, East Lansing, MI 48824 USA (Email: alexliu@cse.msu.edu).

Y. Han is with the School of Information and Communications Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China. (Email: yuhan.uestc@outlook.com).

Y. Chen is with the School of Electronic, Electrical, and Communication Engineering, University of Chinese Academy of Sciences, Beijing, 100190, P.R.China (e-mail: chenyr@ucas.ac.cn).

Digital Object Identifier xxxx

Manuscript received April 19, 2005; revised August 26, 2015.

time slots) per frame, a tag randomly picks up a time slot to respond to the reader using its ID. As the number of tags increases, the maximum system throughput of 0.368 can be achieved asymptotically [7-11] when the frame size is equal to the number of tags queried by the reader. Since the reader cannot obtain the tag cardinality (the number of unread tags) in advance, a cardinality estimation function is integrated into the anti-collision algorithm to dynamically vary the frame size [6-10]. To improve estimation accuracy, most previous methods [5-8] are implemented with high complexity, which are only suitable for scenarios with fixed RFID reader. However, most mobile RFID readers are computation constrained due to their low-cost hardware structure such as single-core microprocessor. Consequently, such anti-collision algorithms with complex estimation method are inefficient in terms of time or energy efficiency for mobile scenarios. Recently, a number of energy-efficient DFSA algorithms have been proposed for the purpose of reducing computational overhead. In [29], the sub-frame based algorithm is proposed to overcome the accumulated estimation error. The tag cardinality is estimated based on the linear relation between number of empty and collision slots statistically counted in a sub-frame. However, since the usage of empirical correlation is not based on theoretical calculation, the accuracy of estimation is not guaranteed. The author in [30] presented an efficient anti-collision algorithm with early adjustment of frame length (EACAEA). Since the estimation and frame size determination depend on one examination of a frame at a specific time slot during each identification round, it can achieve a good compromise between computational complexity and throughput performance [31]. The literature in [32] introduced an Improved Linearized Combinatorial Model (ILCM) to estimate the cardinality at the cost of modest calculation. Since the ILCM adopts a frame-by-frame (FbF) tag quantity estimation method based on slot statistics observed in the previous full frame, the performance of ILCM is limited to the accuracy of a single estimation. Therefore, its performance fluctuates sharply when the tag quantity changes significantly. To achieve the robust performance, the slot-by-slot (SbS) version of ILCM has been presented in [33]. In [34], the authors introduced a DFSA anti-collision protocol which calculates frame length according to cardinality estimation. The estimation mechanism is based on the number of collision slots at k-th slot, where k is obtained iteratively based on a threshold value. The literature in [35] presented a method to identify the time slot distribution selected by tags in advance, and hence reduce the number of total slots by eliminating empty slots. To minimize the total identification time, a fast anti-collision algorithm named timing-aware frame slotted Aloha (TAFSA) is proposed in [36]. The TAFSA updates the frame size according to the timing parameters of a RFID system and thus increases the tag identification rate.

In [37]-[38], some hybrid schemes that combine the advantages of QT-based and Aloha-based algorithms provide better performance. In general, these algorithms can achieve higher system throughput than Aloha-based and QT-based algorithms. However, because of using the bit identification and tracking technology, they are incompatible to the UHF RFID systems. Another type of hybrid algorithms named adaptive binary tree slotted Aloha (ABTSA) [39] has been proposed by incorporating merits of conventional binary splitting and Aloha-based algorithms. The tags in a collided slot will be identified by a conventional binary splitting method immediately, while the remaining tags will wait until the former ones are successfully identified. The ABTSA adjusts the frame size based on the response of tags slot-by-slot. Since the ABTSA can maintain a fine-grained frame size adjustment for the tag cardinality, it can achieve a stable system throughput at about 0.40. The authors in [40] proposed a two-phase anti-collision algorithm named detected sector based DFSA (ds-DFSA) to enhance the identification performance. The highest performance of system throughput peaks at 0.41.

The above work focus on theoretically analysis of MAC protocol for RFID. However, some physical factors such as noisy channel or capture effect may have a serious impact on the performance of RFID tag identification. In existing literatures, there are many efforts to carry out real measurement of RFID performance including bit-level synchronization [41], the tag sensitivity [47], and radio-effect [7, 48]. The authors in [41] verified that the bit-level synchronization is feasible in tag identification process by using the USRP platform and WISP tags. The experimental results in [47] show that the UHF RFID tag has a nonlinear input characteristics, and its input impedance depends on both the operating frequency and received power, which will cause an increase in the number of unidentified tags due to an imbalance between the tag IC and the antenna. The findings in [48] reveal that radio waves propagation has a significantly impact on throughput of UHF RFID system. Furthermore, literatures [7] and [48] attempt to optimize the RFID system parameters through experiments, however, they are unable to apply to more general environmental settings.

In this paper, we first analyze the identification efficiency of the modified binary splitting (MBS) strategy and derive its close-form expression, in order to maximize the identification performance and guarantee the reliability of UHF RFID system. Furthermore, we analyze the grouping model for the modified binary splitting and calculate the optimal grouping coefficient. Finally, the group-based binary splitting algorithm (GBSA) is proposed to maximize the identification performance of the UHF RFID. The performance study shows the significant improvement of system throughput by 42.5% in a RFID system using GBSA. The advantages of the GBSA can be summarized as high system throughput, good robustness (its efficiency is almost independent to the tag cardinality and initial frame length) and low computational complexity.

Our contributions are summarized as follows.

1) We formulate the tag identification process as a grouping problem and provide a series of optimization derivations to obtain the optimal group number. The key technical contribution of these theoretical derivations is to improve identification performance. According to these derivations, we propose a group-based binary splitting anti-collision (GBSA) algorithm and prove that the GBSA has better performance than the prior art.

2) We propose a new strategy to estimate the tag cardinality which is required for the optimization of reading performance.

In the estimation process, the maximum likelihood estimator is applied to compute the cardinality using the statistics of a sub-frame. To reduce the computational complexity, the estimation results are pre-saved in the pooled tables rather than calculated during the identification process.

3) We implement the proposed GBSA algorithm in a practical UHF RFID system, which includes a reader and 20 custom tags. The experiment results show that the proposed GBSA is a suitable candidate for commercial and industrial RFID systems.

II. System Model

The function blocks of GBSA algorithm is described in Fig. 1. As can be observed, the GBSA contains three important function blocks: tag cardinality estimation, optimal grouping factor f_{opt} calculation and individual groups identification. The GBSA starts an identification process with an initialized frame containing a number of time slots. Each tag responds to the reader with its ID in a randomly selected slot. There are three possible outcomes in a given slot: idle, collision and success. The reader makes use of the statistics of idle, collision and success slots to estimate the cardinality and determine the optimal grouping factor f_{opt}. Then the tags in the reader vicinity will be divided into $N = n{\cdot}f_{opt}$ groups. In each group, the reader identifies tags using the MBS strategy. By applying the MBS scheduling, the idle slots occurred in the conventional binary splitting can be eliminated. Moreover, 1-bit random binary number generator (RBNG) R is introduced to pre-split contending tag set. Since the idle slots in the splitting process and the time duration used for collision arbitration are eliminated, the system throughput and time efficiency can be improved. However, existing UHF RFID standards, such as EPC C1 Gen2 or ISO 18000-6B, can only support DFSA or BS operation, modification of current commercial RFID hardware has to be done to enable the GBSA. The modification can be summarized as follows. 1) Tags need to add a binary random number generator and a counter to record the slot index, 2) A reader needs to add extra custom commands to support the functionality of GBSA. Although extra circuit complexity is introduced to adapt to the proposed solution, it is negligible relative to the overall circuit scale of modern tags [41-42] and makes worthwhile contribution to significant performance improvement.

Although the GBSA first divides the whole tag set into several groups and then identifies them one by one, the reader is unable to identify all subsets of tags simultaneously due to current RFID standard and framework. Since GBSA is stemmed from Aloha algorithms, its identification performance is related to the tag cardinality and the frame size. In order to maintain high efficiency, GBSA needs to set an appropriate frame size for the cardinality. Since readers typically have no knowledge of number of tags in advance, an accurate tag cardinality estimation method is necessary for GBSA algorithm.

III. Tag Cardinality Estimation Method

As mentioned in Section 2, the number of tags is unknown in most application scenarios, the reader thus needs to estimate

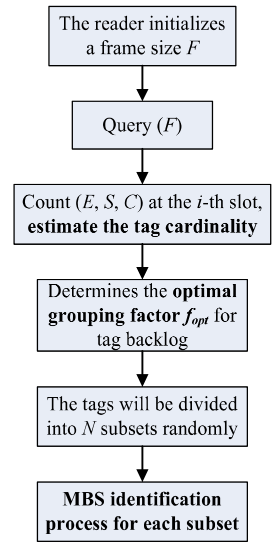


Fig. 1. The function block diagram of the GBSA

the cardinality in order to implement the proposed GBSA. Here we refer to the maximum a posteriori probability (MAP) [5] method to calculate the cardinality of tag population based on feedbacks from a sub-frame. Although MAP can achieve an accurate estimation, the high computational overhead hinders its application on low-cost RFID platforms [29][31-34], such as single-core ARM-based readers. In the proposed estimation method, we use pooled tables to pre-store intermediate variable of estimation results. Given the limited sub-frame size and number of variables needed in the tables, the proposed estimation strategy should be space-efficient and implementable.

In the proposed GBSA, a full frame consists of multiple sub-frames. Since tags are uniformly distributed in the full frame, the expected number of tags allocated into each sub-frame are statistically equal. Therefore, the tag estimation can be calculated based on the first sub-frame. Considering n tags are allocated in F slots, the probability that idle slot occurs e times, success slot occurs s times and collision slot occurs c times in a sub-frame F_{sub} can be expressed as [29, 31]

$$P\left(F_{sub},\ e,\ s,\ c\right) = \left(\frac{F_{sub}!}{e!s!c!}\right) \times P_0\left(e\right) \times P_1\left(s|e\right) \times P_2\left(c|e,\ s\right)\ . \tag{1}$$

where $P_0\left(e\right)$, $P_1\left(s|e\right)$, and $P_2\left(c|e,\ s\right)$ are the probabilities of idle, success, and collision slot, and can be calculated as

$$P_0\left(e\right) = \left(1 - \frac{e}{F_{sub}}\right)^n , \tag{2}$$

$$\begin{aligned} P_1\left(s|e\right) &= \left(\begin{array}{c} n \\ s \end{array}\right) \times \left(\tfrac{s}{F_{sub}-e}\right)^s \times \left(1 - \tfrac{s}{F_{sub}-e}\right)^{n-s} \times \tfrac{s!}{s^s} \\ &= \left(\begin{array}{c} n \\ s \end{array}\right) \times \left(\tfrac{(F_{sub}-e-s)^{n-s}}{(F_{sub}-e)^n}\right) s!\,, \end{aligned} \tag{3}$$

$$\begin{aligned} P_2\left(c|e,\ s\right) = \sum_{k=0}^{c} \sum_{v=0}^{c-k} (-1)^{(k+v)} \times \left(\begin{array}{c} c \\ k \end{array}\right) \times \left(\begin{array}{c} c-k \\ v \end{array}\right) \\ \times \tfrac{(n-s)!}{(n-s-k)!} \tfrac{(c-k-v)^{(n-s-k)}}{c^{(n-s)}}\ , \end{aligned} \tag{4}$$

The estimated number of tags involved in a sub-frame can be determined when the probability of Eq. (1) is maximized. That is, the estimated $\hat{n}_{sub} = n$ when $P(F_{sub}, e, s, c)$ is maximum. Then, the estimated cardinality involved in the full frame is calculated as

$$\hat{n}_{est} = \hat{n}_{sub} \times \frac{F}{F_{sub}}. \tag{5}$$

It is noted that if the estimated cardinality is not in the optimal range of current full frame, the frame size requires to be updated. In other words, a new identification round with an updated frame and sub-frame is required. Such update will repeat until an appropriate one is determined. Since F_{sub} accounts only a small segment of original frame, the performance degradation derived from estimation error in sub-frame can be neglected. The optimal frame size for different estimated tag cardinality range can be summarized in Tab. I by using the existing solutions [5, 8, 29-30, 37].

TABLE I
RELATION BETWEEN OPTIMAL FRAME SIZE AND TAG CARDINALITY RANGE

Estimated tag cardinality range (n_1 to n_2)	Optimal frame size (F_{opt}=2^Q)	Q ($\log_2^F$)
1 to 3	2	1
4 to 5	4	2
6 to 11	8	3
12 to 22	16	4
23 to 44	32	5
45 to 89	64	6
90 to 177	128	7
178 to 355	256	8
356 to 710	512	9
711 to 1420	1024	10

TABLE II
THE RECOMMENDATION SETTING OF F_{sub}

F	**8∼16**	**32∼64**	**128∼256**	**512∼1024**	**>1024**
F_{sub}	4	8	16	32	64

To reduce computational complexity, the estimated results of tag cardinality in a sub-frame can be stored in the preset look-up table (LuT). Although the proposed estimation strategy requires additional storage to store the LuT, it can use the sub-frame structure to limit the table size. Meanwhile, the size of sub-frame should also be seriously considered. If sub-frame size is too large, the optimal grouping factor calculation will consume too many slots, degrade the whole performance of GBSA and increase storage space of the table. As a contrast, if sub-frame size is too small, the accumulated estimation error may be significant which leads to improper frame size calculation. Referring to [29], we recommend sub-frame size as listed in the Tab. II.

It is noted that if collisions occupy all slots in a sub-frame, the cardinality estimated by the MAP may become rather large. In order to control the estimation error in such a case, we limit the frame size adjustment as $8 \cdot F_{sub}$. Also, since each estimation result of a sub-frame MAP table is stored in one Byte, the value cannot exceed 255. Therefore, the maximum estimated cardinality in a sub-frame is $\min\{8 \cdot F_{sub}, 255\}$. The maximum occupied memory size of tables can be calculated as $64 \cdot 65/2$ Bytes when the sub-frame size is equal to 64. Since there are five tables ($F_{sub} = 4, 8, 16, 32, 64$) in the estimation, the total size to accommodate all tables can be computed as 2790 Bytes. Considering a handheld RFID reader embedded with ARM processor, such as AT91SAM256 with 256 Kbytes of internal high-speed flash, it should be sufficient to store the required LuT [29].

TABLE III
AN IDENTIFICATION EXAMPLE USING MBS TO IDENTIFY THREE TAGS

Slot	Tag A (T_c, R, F)	Tag B (T_c, R, F)	Tag C (T_c, R, F)	Action
1	(0, 1, 1)	(0, 1, 1)	(0, 1, 1)	ID collided
2	(0, 1, 0)	(0, 0, 0)	(0, 1, 0)	R collided
3	(1, x, 0)	(0, 0, 1)	(1, x, 0)	B is identified
4	(0, 1, 1)	(-1, x, x)	(0, 1, 1)	ID collided
5	(0, 0, 0)	(-1, x, x)	(0, 1, 0)	R collided
6	(0, 1, 1)	(-1, x, x)	(1, x, 0)	A is identified
7	(-1, x, x)	(-1, x, x)	(0, 0, 1)	C is identified

IV. MBS IDENTIFICATION STRATEGY AND OPTIMAL GROUPING FACTOR

According to the above estimation method, the reader can accurately estimate the number of tags in its coverage range. Assume there are n tags in the reader vicinity waiting to be identified, GBSA divides them into N groups on average according to the tag cardinality estimation and will further apply the MBS algorithm on individual group. In order to derive the optimal grouping factor for the best identification performance, we first introduce the MBS strategy.

A. Modified Binary Splitting

In the MBS algorithm, each tag has a binary flag indictor F, T_c and RBNG R. All tags are initialized as $T_c = R = F = 0$. The reader owns a counter R_c at the beginning of the reading process. After queried by the reader, a tag will respond to it when $T_c = 0$. If $F = 0$, the tag responds with R signal, otherwise with its tag ID. The flowchart of MBS is described in Fig. 2. When R_c reaches a negative value, the identification process will be ended. To illustrate the proposed MBS strategy, Tab. III shows an identification process using MBS to identify three tags A, B, C. It is noted that each tag generates a random R value at each slot. As can be seen from the example, the MBS strategy can eliminate idle queries which exist in conventional BS when more than one tag generate $R = 1$ during an identification process. Moreover, by adopting 1-bit R signal, the MBS can save collision arbitration time because the time duration of R-collision slot is significantly less than that of ID-collision slot. As the number of tags increases, the advantages of MBS strategy become more obvious.

B. System Throughput of the Modified Binary Splitting

Theorem 1. *Let n denotes the cardinality of tag population within the reader's coverage, N_n denotes the total number*

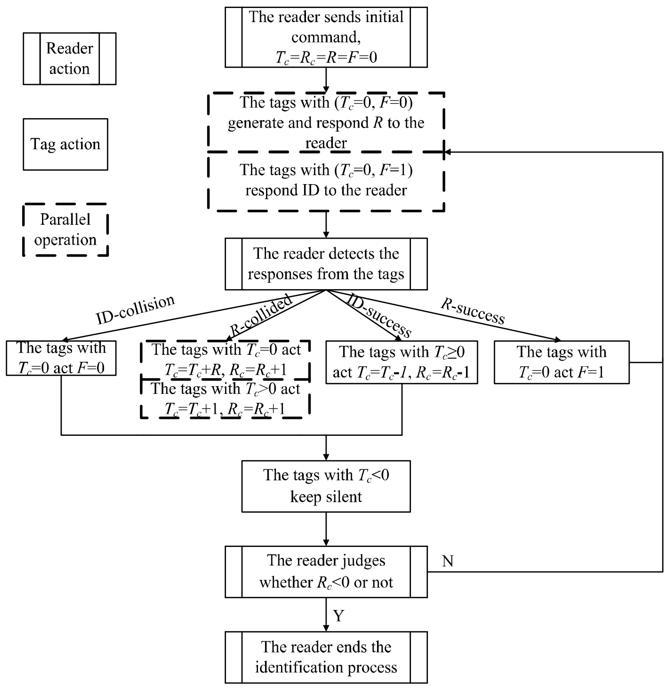


Fig. 2. The flowchart of the proposed MBS strategy

of slots consumed to identify all tags and $E(N_n)$ *denotes the expected number of slots to identify all tags, the system throughput of the MBS algorithm* T_{sys} *can be derived as*

$$T_{sys}(n) = \frac{\frac{n\left(2^{n-1}-1\right)}{2^{n-1}}}{\frac{2}{2^n}+\sum_{x=1}^{n-1}\frac{C_n^x}{2^n}\left(E(N_{x+1}^*)+E(N_{n-x})\right)} . \quad (6)$$

where N_{x+1}^* *is the number of slots to identify these* $x+1$ *tags from sequence* $\underbrace{00...0}_{x}1$.

Proof: See the Appendix A. □

For example, when $n=2$ the expected number of slots by GBSA can be computed as

$$\begin{aligned} E\left(N_2\right) &= \frac{\frac{2}{2^2}+\frac{C_2^1}{2^2}\left(E(N_2^*)+E(N_1)\right)}{\frac{2^{2-1}-1}{2^{2-1}}} \\ &= 2\times\left(\frac{2}{4}+\frac{2}{4}\times\left(E\left(N_2^*\right)+E\left(N_1\right)\right)\right) , \end{aligned} \quad (7)$$

According to the definition of $E\left(N_2^*\right)$ and $E\left(N_1\right)$, we have

$$E\left(N_2^*\right) = 2 , \quad (8)$$

$$E\left(N_1\right) = 1 , \quad (9)$$

According to Eqs. (7)-(9), we can have

$$E\left(N_2\right) = 2\times\left(\frac{1}{2}+\frac{1}{2}\times(2+1)\right) = 4 . \quad (10)$$

Therefore, the system throughput of the MBS algorithm to identify two tags can be computed as $T_{sys}\left(2\right) = \frac{2}{4} = 0.5$.

C. The Optimal Grouping Factor

In this subsection, we derive the optimal grouping factor to maximize the identification performance of GBSA.

Lemma 1. *Let* S_n *denotes the total slots consumed by GBSA to identify* n *tags, the system throughput of GBSA can be expressed as*

$$T_{sys}^{GBSA} = \frac{n}{\sum_{k=0}^{n} N\times P_k\times E\left(N_k\right)} . \quad (11)$$

Proof: See the Appendix B. □

In order to maximize the performance of the proposed GBSA, the optimal grouping factor should be derived. In Eq. (11), the value of k is between 0 to n. However, we can set its upper value as 20, since the value of $E(B_k)$ becomes negligible when $k>20$. The system throughput can be approximated as

$$\begin{aligned} T_{sys}^{GBSA} &= \frac{n}{\sum_{k=0}^{n} N\times P_k\times E(N_k)} \\ &\approx \frac{n}{N\sum_{k=0}^{20} P_k\times E(N_k)} , \end{aligned} \quad (12)$$

According to Eq. (12), the optimal grouping factor can be derived as follows. We denote the group number N as

$$N = n\times f , \quad (13)$$

where, $f\in[0.3,\ 1.3]$ is defined as the grouping factor. Furthermore, by using $f=N/n$, Eq. (12) can be rewritten as

$$\begin{aligned} T_{sys}^{GBSA} &\approx \frac{n}{N\sum_{k=0}^{20} P_k\times E(N_k)} \\ &\approx \frac{1}{\frac{N}{n}\left(1+\sum_{k=2}^{20} P_k\times(E(N_k)-1)\right)} \\ &= \frac{1}{\frac{N}{n}\left[1+\sum_{k=2}^{20}\frac{1}{k!}\frac{n(n-1)\ldots(n-k+1)}{N^k}(1-\frac{1}{N})^{N\times\frac{n-k}{N}}(E(N_k)-1)\right]} \\ &\approx \frac{1}{f\left[1+\sum_{k=2}^{20}\frac{1}{k!}f^{-k}(\frac{1}{e})^{\frac{1}{f}}(E(N_k)-1)\right]} , \end{aligned} \quad (14)$$

Denote that

$$g\left(f\right) = f\left[1+\sum_{k=2}^{20}\frac{1}{k!}f^{-k}\left(\frac{1}{e}\right)^{\frac{1}{f}}\left(E(N_k)-1\right)\right] , \quad (15)$$

The optimal grouping factor can be expressed as

$$\begin{aligned} f_{opt} &= \min_{f\in[0.3,\ 1.3]} g\left(f\right) \\ &= \min_{f\in[0.3,\ 1.3]}\left[f\left(1+\sum_{k=2}^{20}\frac{1}{k!}f^{-k}(\frac{1}{e})^{\frac{1}{f}}\left(E(N_k)-1\right)\right)\right] , \end{aligned} \quad (16)$$

By taking the first derivative of $g(f)$ with respect to f and have it equals to zero, that is

$$\begin{aligned} g'\left(f\right) &= 1+\sum_{k=2}^{20}\frac{1}{k!}\left[-(k-1)f^{-k}\right. \\ &\quad \left.+f^{-k-1}\right]\left(\frac{1}{e}\right)^{\frac{1}{f}}\left(E(N_k)-1\right) \\ &= 0 , \end{aligned} \quad (17)$$

We can obtain the optimal value by applying the simple bisection search or Newton's methods to solve the above non-linear equation with one variable. The result is $f_{opt} = 0.7273$

for $g''(f_{opt}) > 0$. Therefore, the optimal group number N_{opt} can be calculated as

$$N_{opt} = f_{opt} \times n \approx 0.73n\,. \tag{18}$$

V. The Proposed GBSA and its Performance Analysis

A. Algorithm Description

By combining the tag cardinality estimation, the optimal grouping strategy and MBS identification mechanism, the pseudo-code of GBSA can be described in Algorithm 1, where e, s and c are the number of idle, success and collision slots in a sub-frame. F_{sub} is the size of the sub-frame. Since F_{sub} is a portion of the full frame, it varies with the frame size during the identification process. $\hat{n}_{est}$ is the estimated number of tags before the current identification round. According to Eq. (5), the reader will interrupt the ongoing frame if $\hat{n}_{est}$ does not fall into the optimal range of current frame size. In other words, an identification round with updated frame and F_{sub} is required. It is noted that the estimated tag cardinality is $\hat{n}_{est} - s$ during the current identification round.

Algorithm 1 GBSA Reader Operation

Initialize F_{ini}, F_{sub}, e, s, c;
GBSA (F_{ini}, F_{sub});
function GBSA (F_{ini}, F_{sub})
Broadcast Query/QueryAdj with F and F_{sub}
$e = s = c = 0$; $i = 1$;
while $i \le F_{sub}$ **do**
  Receive tag response slot by slot;
  if only one tag response **then**
    identify the tag and $s++$; $i++$;
  else if no tag response **then**
    $e++$; $i++$;
  else
    $c++$; $i++$;
  end if
end while
Count (s, s, c) and estimate n_{est};
if $\hat{n}_{est}$ is not in the optimal range of current F **then**
  $n_{rest} = \hat{n}_{est} - s$, update new F, F_{sub} and goto 3;
else
  $N_{opt} = round(0.7273 * n_{rest})$ and PUSH[0:N_{opt}] to the stack;
end if
Tag_identification (N_{opt});
function Tag_identification (N_{opt})
if stack is empty **then**
  identification process ends;
else
  $index$=POP(); MBS($index$);
end if
function MBS($index$)
while $R_c \ge 0$ **do**
  Receive tag response slot by slot
  if R-success **then**
    the tags with $T_c = 0$ act $F = 1$;
    if ID-collision **then**
      the tags with $T_c = 0$ act $F = 0$;
    else if ID-success **then**
      the tags with $T_c \ge 0$ act T_c++, and R_c--
    end if
  else if R-collided **then**
    the tags with $T_c = 0$ act $T_c = +R$, and the tags with $T_c > 0$ act T_c++; R_c++
  end if
end while

It is noted that in GBSA, an initial frame size may not be optimal at the beginning. However, the frame size will be adjusted by the strategy described in Algorithm 1. After the optimal frame size is determined, the optimal grouping strategy and MBS nested in GBSA can help achieve the optimal efficiency.

B. Performance Analysis of GBSA

In this subsection, we analyze the system throughput, the total slots to identify all tags in GBSA and time efficiency. Herein, the total slots is calculated as total sum of idle, success and collision slots. Specifically, since the collision slots of GBSA can be categorized into two classes: ID-collision and R-collision, the time efficiency can be defined as [16, 25, 33]

$$\eta = \frac{n \times T_{ID}}{\begin{array}{c}(n \times T_{succ} + N_{idle} \times T_{idle} \\ + N_{coll} \times T_{coll} + N_{R-coll} \times T_{R-coll})\end{array}}\,. \tag{19}$$

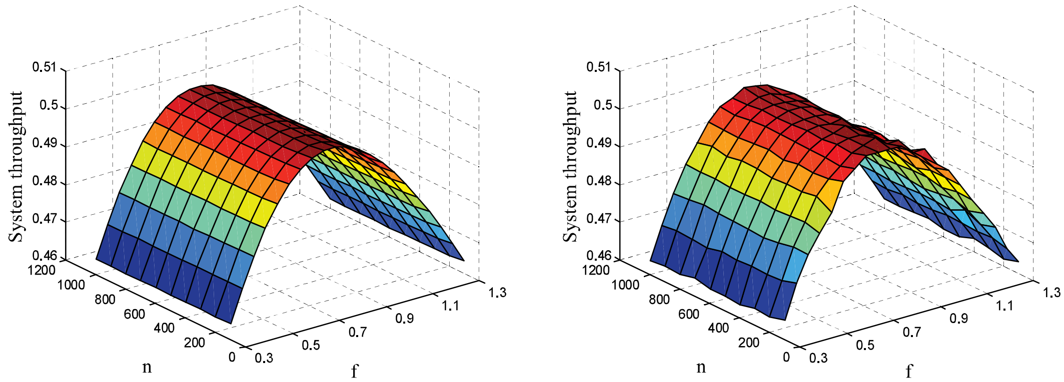
where T_{ID} denotes the time interval required to transmit a tag's ID. n, N_{idle}, N_{coll} and N_{R-coll} denote the number of idle, success, ID-collision and R-collision slots, respectively. T_{idle}, T_{succ}, T_{coll}, and T_{R-coll} represent the time intervals of above four types of slot and they are measured by the reader during the identification process.

Theorem 2. *Under the perfect condition (the cardinality of tag population is known to the reader), the optimal system throughput of GBSA to identify n tags is*

$$T_{sys}^{GBSA} \approx 0.5022. \tag{20}$$

Proof: See the Appendix C. □

It is noted that Theorem 2 reveals the upper performance bound of GBSA under perfect condition. We can verify the effectiveness and reliability of the proposed solution under imperfect conditions through simulations. Fig. 3 provides simulation and theoretical results of system throughput with different grouping factors. The experiment is conducted through exhaustive Monte-Carlo with 1000 iterations. As can be observed, the simulation results are very closed to the theoretical value, which proves that the theoretical analysis is highly accurate. Although the number of tags varies from 100 to 1000, the system throughput almost maintains at a stable value. The optimal grouping factor falls into (0.7, 0.8). Specifically, the system throughput can peak at about 0.5022 when the grouping factor is about 0.73. Fig. 3 also verify the effectiveness of the analysis concerning the optimal grouping factor in Section 4.



(a) Analytical results of system throughput with different f (b) Simulation results of system throughput with different f

Fig. 3. Comparison of analysis and simulation results for the system throughput

Lemma 2. *For any n tags, the expected number of R-collision slots in GBSA is*

$$E\left(N_{R-coll}\right) \approx 0.456n\,. \tag{21}$$

Proof: See the Appendix D. □

Theorem 3. *Under the perfect condition (the cardinality of tag population is known to the reader), the optimal time efficiency of GBSA to identify n tags can be expressed as*

$$E\left(\eta^*_{GBSA}\right) \approx \frac{T_{ID}}{\begin{array}{l}(T_{succ} + 0.1839 \times T_{idle} + 0.3513 \times T_{coll}\\ +0.456 \times T_{R-coll})\end{array}}\,. \tag{22}$$

Proof: See the Appendix E. □

VI. Simulation Results

Various metrics including system throughput, average time to identify a tag and time efficiency are taken into account to evaluate and compare GBSA performance with existing state-of-the-art methods including EACAEA [30], ds-DFSA [40], ABTSA [39], PSR [43] and MAP [5] over extensive Monte Carlo simulations. We setup high dense network scenarios with a single reader and a variety of tags from 100 to 1000. Same as in [5-8, 22-28, 29-41], the wireless channel has no capture effect and noise.[1]

All simulation results have been obtained by averaging over 1000 iterations. The time parameters used in simulations are summarized in Tab. IV, which align with EPC C1 Gen2 standard [4].

[1]The reasons we do not consider them are two-fold: one is that the noise may cause detection errors which will interfere the MAC mechanism we discuss in this paper. Another one is that when the distance between the reader and tags is smaller than 10 m in indoor environment, the SNR of the passive RFID systems will be greater than 15 dB, and the bit error probability is smaller than 10^{-6} [44]. The transmission bit error can be negligible so that it has almost no effect on the identification process. Furthermore, according to the analysis of existing literatures [20], if the capture effect occurs, the original collision slot will be turned into a success slot, which accelerates the identification process. In such a case, the performance of all algorithms will be enhanced, which will be misleading the performance analysis of MAC protocols. Further proof can also be found in literatures [45-46].

TABLE IV
Simulation Parameters according to EPCglobal C1 Gen2

Parameters	Value	Parameters	Value
Reader-to-tag data-0	1 Tari	RTcal	37.5 μs
Reader-to-tag data-1	2 Tari	TRcal	50 μs
Reader-to-tag rate	80kbps	T1	62.5 μs
Tag-to-reader rate	160kbps	T2	62.5 μs
Tpri	6.25 μs	T3	100 μs
Tari	12.5 μs	Probe	4bits
feedback	3bits	RN16	16bits
Query	22bits	ID	96bits
QueryAdj	9bits	Ack	18bits
R-T Preamble	112.5 μs	QueryRep	4bits
T-R Preamble	37.5 μs	Framesync	62.5 μs

Fig.4 compares system throughput of various algorithms under different initial frame size. As can be observed, the Aloha-based algorithms including EACAEA, MAP and ABTSA are more sensitive to initial frame size. Among these algorithms, MAP is the most sensitive to frame size. When the number of tags is much larger than the size of frame, MAP is unable to tune to an appropriate frame size fitted for unread tags and thus causes performance degradation. That is to say, MAP cannot cope with diverse tag population in order to provide stability and scalability. Compared to FbF tag estimation used in MAP, EACAEA adopts the early observation mechanism which allows the reader to end identification when the frame size is not appropriate, hence it can guarantee more stable performance. ABTSA can also improve the stability performance by using the SbS estimation mechanism which, however, introduces high costs because of slot by slot frame size calculation and adjustment. Such estimation may also dramatically increase computational complexity when it is implemented on a handheld reader with limited computational resource. From the implementation point of view, a compromise between estimation accuracy and computational complexity should be considered. To reduce the computational complexity, ds-DFSA introduces the frame breaking policy for size adjustment. ds-DFSA is capable of interrupting inappropriate frame through observations of a fraction of frame in order to achieve robustness. Since the

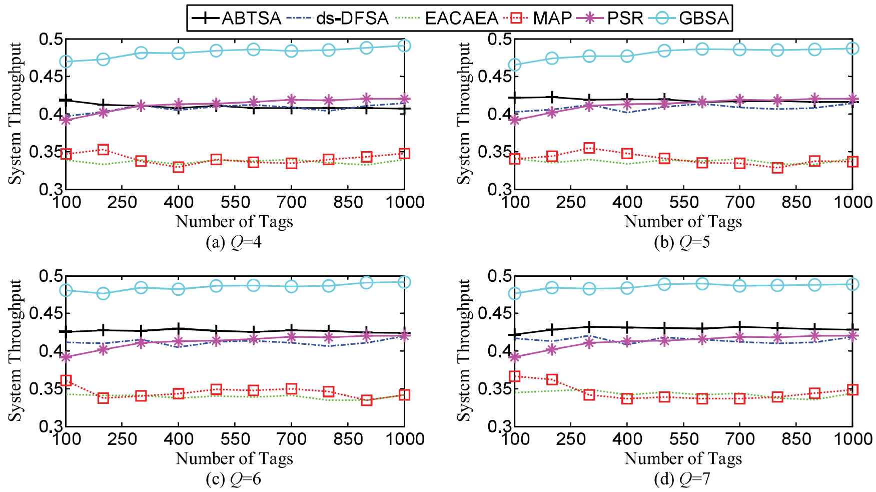


Fig. 4. Comparison of system throughput for various algorithms

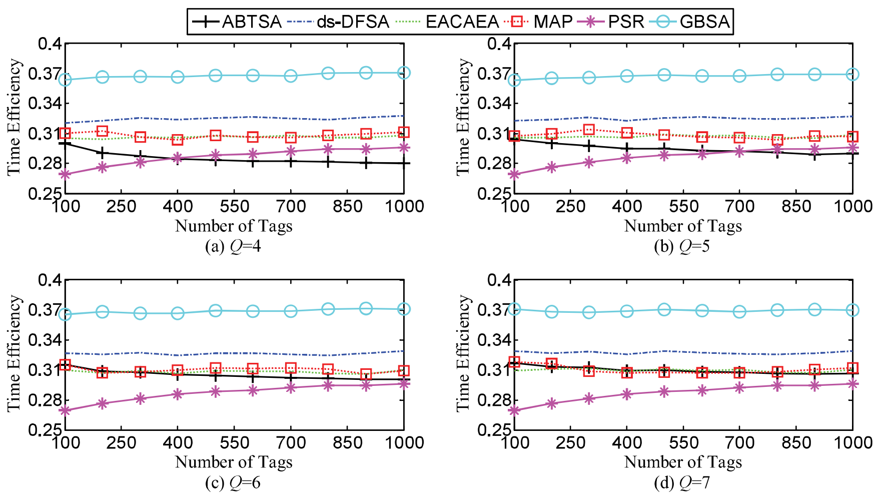


Fig. 5. Comparison of time efficiency for various algorithms

estimation is performed on a small proportion of full frame, the performance degradation resulted from estimation error can be neglected. PSR is not an Aloha-based solution, thus its performance keeps the same and is not affected by varying initial frame size.

Also from Fig.4, the average system throughput of six algorithms from the highest to the lowest are GBSA, ABTSA, PSR, ds-DFSA, MAP and EACAEA. The conventional Aloha-based algorithms such as MAP and EACAEA can only improve estimation accuracy or reduce computational complexity. Hence, their system throughput is below 0.368. For MAP and EACAEA, their system throughput are around 0.34. For ds-DFSA, ABTSA and PSR, their system throughput are above 0.41. ds-DFSA adopts the divide-and-conquer policy in each collided slot to improve system throughput. ABTSA solves collided slots by using binary splitting method and can reach a higher system throughput than the traditional Aloha-based algorithms. PSR introduces a parallel binary splitting strategy to decrease collision slots in order to improve system throughput. The average throughput of GBSA is 0.4835 which outperforms all reference methods. Tab. V also summarizes average throughput of all methods and their percentage improvements over a benchmark method (EACAEA) when the frame size is initialized to 16, 32, 64, and 128, respectively.

TABLE V
COMPARISON OF SYSTEM THROUGHPUT FOR VARIOUS ALGORITHMS

Method	Average ($100 \leq n \leq 1000$)	Improvement
EACAEA	0.3392	-
MAP	0.3428	1.06%
ds-DFSA	0.4106	21.1%
PSR	0.4126	21.6%
ABTSA	0.4211	24.2%
GBSA	0.4835	42.5%

To further illustrate the advantage of GBSA, we show time efficiency of various algorithms in Fig.5. As compared with Fig.4, most algorithms show discrepant performance under two different performance metrics. For example, although the system throughput of PSR is higher than ds-DFSA, MAP and EACAEA, its time efficiency is lower than these Aloha-based

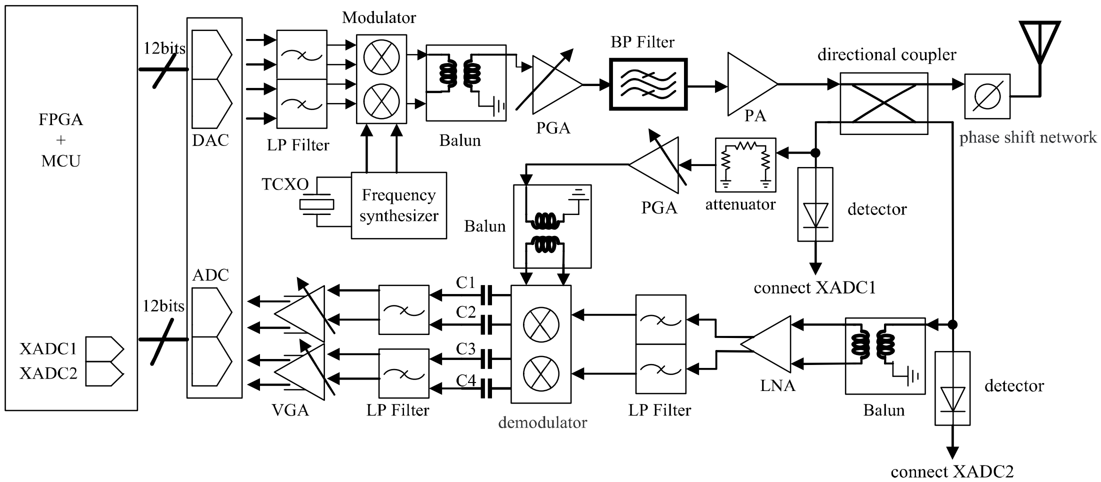


Fig. 6. The architecture diagram of the UHF RFID reader

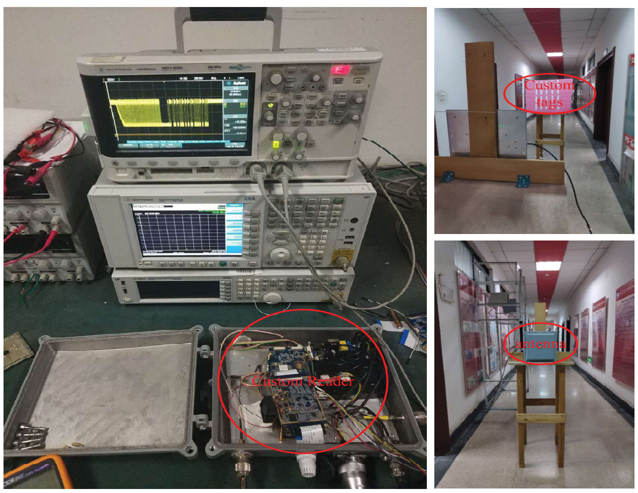


Fig. 7. RFID hardware setup used in the experiments

algorithms because the PSR adopts the ID collision arbitration which takes longer time duration than RN16-collided slot during identification process. Similarly, the time efficiency of ABTSA is lower than that of ds-DFSA, MAP and EACAEA. Since idle slots in the conventional binary splitting can be eliminated by the schedule of the proposed strategy and the time duration used for collision arbitration can be further reduced, GBSA can achieve the best time efficiency compared to other algorithms. Specifically, GBSA achieves average time efficiency of 0.3683 and performs better than PSR, ABTSA, EACAEA, MAP and ds-DFSA by up to 28.4%, 23.3%, 19.7%, 19.1% and 12.4%, respectively.

VII. Experimental Results using a Practical RFID Testbed

To further evaluate reading performance of the proposed GBSA algorithm in a practical UHF RFID system, we conduct experiments using a self-developed testbed in an indoor environment [8]. The prototype of GBSA is implemented on a fixed RFID reader (developed by our Lab) and custom tags (which supports both standard EPC C1 Gen2 and our proposed protocol). The reader used in the experiment is designed to support the EPC C1 Gen2 standard protocol and our proposed protocol. Specifically, high isolation is achieved by a directional coupler based double-tuning RF transmit-receive circuit with a compact structure, which alleviates the linearity requirements of the receiver front-end. By utilizing the coupled signal from the directional coupler as the local-oscillation signal of the demodulator, the correlation between the local-oscillation signal and the RF self-jammer is improved, and the residual phase noise of the down-converted baseband signal is reduced. The maximum RF output power of the reader can reach 30 dBm, and the 8 dB gain circularly polarized antenna can achieve an EIRP of 38dBm. In addition, the reader's receiver sensitivity reaches -70dBm, which fully meets the performance specifications of the EPC C1 Gen2 standard. The detailed structure of the reader used in the experiments as described in the Fig. 6.

The reader is equipped with ARM Cortex A9 processor which is a 32-bit reduced instruction set (RISC) processor with a maximum operating frequency of 1 GHz and an off-chip memory 512M to ensure high speed and stable operation of the program. The enrich interfaces include UART, JTAG, ETH and USB. Tags are programmed to support the custom commands transmitted from the reader. The entire hardware environment is captured in Fig. 6, which includes a reader module, power supply, customs tags, an antenna, an oscilloscope and a host computer. In the experiments, we fix the distance between the reader antenna and tags to 1.3m so that all tags are in the far field of the antenna. The anti-collision algorithm is implemented in RFID firmware using C programming language. Tab. VI lists the link parameters configured for radio frequency communications between the reader and tags. It is also noted that same to the simulations, the reader does not know the exact number of tags in the experiments.

The experiments are carried out by placing custom tags in the interrogation zone of the reader antenna with a fixed transmission power. We evaluate and compare the performance of standard Q-algorithm used in EPC C1 Gen2, commercial

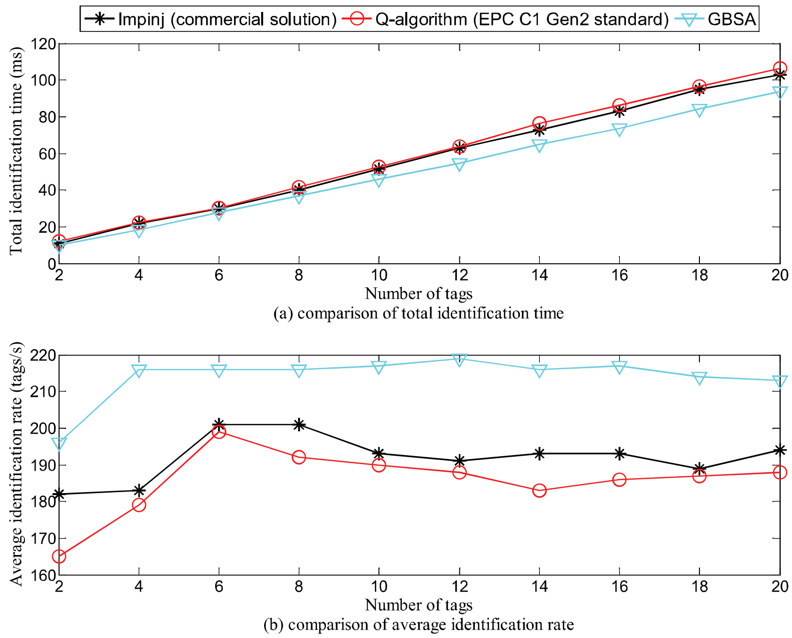


Fig. 8. The comparison of experimental results

TABLE VI
THE LINK PARAMETERS SETTING BETWEEN THE READER AND TAG COMMUNICATION

Parameter	Value
Frequency (MHz)	912.5
BLF (kHz)	250
Modulation	PR-ASK
Deviation (Hz)	20
Channel width (KHz)	250
RTcal (μs)	62.5
TRcal (μs)	85.33
DR	64/3
Tari (μs)	25
TRExt	1
T->R Coding	Miller-4

anti-collision solution Impinj and the proposed GBSA. In order to ensure validity and reliability of observations, we average experiment results from 50 repeated tests per each experiment. To analyze the performance in a practical RFID system, we focus on two metrics: 1) total identification time, defined as the total time taken to successfully identify all tags in a given set, and 2) average identification rate, defined as the number of tags identified per second.

Fig. 8 shows the experimental results by using Q-algorithm, Impinj algorithm and GBSA algorithm to identify the same number of tags in the same time period. As can be observed from Fig. 7 (a), the proposed GBSA reduces the total identification time by an average of 13.09% and 10.44% compared to Q-algorithm and Impinj algorithm. Similarly in Fig. 7 (b), the proposed GBSA improves average identification rate by an average of 15.2% and 11.5% compared to both algorithms. The observed experimental results verify that the proposed GBSA algorithm outperforms the commercial anti-collision solutions constantly in the practical RFID system.

It is noted that in our test environment, the influence of some physical factors (includes position of tags, materials of tags, etc.) on the MAC performance are not considered. To further illustrate such factors, we placed the tags inside the box which was placed on a small trailer as an example. We changed the distance between the reader and box from 1 m to 5 m in step of 1 m, and set the test time as 2 minutes for a single scenario. The experimental scenario is captured in Fig. 9. We record the average identification rate under the scenario in the Tab. VII. We can see that the identification rate varies with the reading distance. Observed from the results, when the tags are placed inside a box, the reading performance is worse than non-obstructing case as in the Fig. 7.

Fig. 9. The experimental scenario when tags inside a box

The fundamental reason behind the results in Tab. VII is that the physical layer factors (materials, capture effect, noise, etc.) can change the sensitivity of the tag, thus affect the reading performance. Moreover, under any aforementioned condition, the performance of all MAC protocols will be affected. The

TABLE VII
COMPARISON OF IDENTIFICATION RATE UNDER DIFFERENT DISTANCES WHEN TAGS INSIDE A BOX

Distance between the reader and box	Average identification rate
1 m	188.4 tags/s
2 m	106 tags/s
3 m	79.5 tags/s
4 m	46.2 tags/s
5 m	52.1 tags/s

test environment in the manuscript is fair and reasonable to all comparative protocols. Finally, because the focus of this paper is on MAC layer, the impact of these physical layer factors is beyond the scope of our research.

VIII. CONCLUSION

In this paper, we have proposed an enhanced collision resolution approach named GBSA to improve the performance of MAC layer of UHF RFID. Specifically, we have designed a low-cost cardinality estimation function suitable for hand-held RFID reader. The closed-form formula of the system throughput of MBS and the optimal grouping factor have also been derived to support the implementation of GBSA. Both theoretical analysis and simulation results have been shown that the proposed GBSA algorithm is superior than the reference algorithms in system throughput and time efficiency. We have also supplemented real tests of the proposed solution and further verified the effectiveness of GBSA in a practical RFID system compared to existing commercial solutions. Such acquired new insights of this study can provide a precise guideline for efficient designs of practical and reliable RFID communications systems. Hence these results will potentially have a broad impact across a range of areas, including supply chain management, inventory control and asset tracking.

IX. ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundation of China (No.61802196); the Natural Science Foundation of Jiangsu Province (No.BK20180791); the Natural Science Foundation of Jiangsu Higher Education Institutions of China (No.17KJB510036); and the Startup Foundation for Introducing Talent of NUIST. This work is also supported in part by Soft Science Program of China Meteorological Administration, the Priority Academic Program Development of Jiangsu Higher Education Institutions. We would like to thank editor Dr. Dania Marabissi and the anonymous reviewers for their insights that improved the article significantly.

APPENDIX A
PROOF OF THEOREM 1

According to the definition of system throughput, T_{sys} can be expressed as

$$T_{sys} = \frac{n}{E\left(N_n\right)}. \tag{23}$$

Considering n tags in the reader vicinity waiting to be identified, the R values of these n tags can be represented as a binary sequence "$R_1R_2...R_n$", which is initialized to zeros. Obviously, since all tags are allowed to be transmitted in the first slot, collision will be detected. If the feedback is ID-collision, each tag will act $F=0$, otherwise each tag will generate binary number and add it to its RBNG.

For n tags, there have 2^n possible RBNG sequences after the first collision. To derive the system throughput to identify n tags, we define $N_{\underbrace{a_1a_2........a_n}_{\substack{a_1=0\ or\ 1\\ for\ 1\le i\le n}}}$ as the required slots to identify n tags from the sequence $\underbrace{a_1a_2........a_n}_{\substack{a_i=0\ or\ 1\\ for\ 1\le i\le n}}$. The probability distribution is expressed as follows

$$\begin{cases} & probability & required\ slots \\ 00......0 & 1/2^n & 1+N_n \\ \underbrace{a_1a_2......a_n}_{\substack{a_i=0\ or\ 1,\ 1\le i\le n \\ \sum_{i=1}^{n} a_i=y,\ 1\le y\le n-1}} & C_n^y/2^n & 1+N_{\underbrace{00..0}_{x}\underbrace{11..1}_{y}}{}_{\substack{\\ x+y=n,\ x\ge 1,\ y\le n-1}} \\ ...... & & \\ 11......1 & 1/2^n & 1+N_n \end{cases} \tag{24}$$

Obviously, $E(N_{\underbrace{a_1a_2......a_n}_{\substack{a_i=0\ or\ 1,\ 1\le i\le n \\ \sum_{i=1}^{n} a_i=y,\ 1\le y\le n-1}}}) = E(N_{\underbrace{00...0}_{x}\underbrace{11...1}_{y}}{}_{\substack{x+y=n\\ x\ge 1,\ y\le n-1}})$, in order to calculate $N_{\underbrace{00...0}_{x}\underbrace{11...1}_{y}}$, we define the required slots from sequence $\underbrace{00...0}_{x}1$ as N^*_{x+1}. After reading $N^*_{x+1}-1$ slots, the count sequence $\underbrace{00...0}_{x}1$ will become sequence (0). Meanwhile, the count sequence $(\underbrace{00...0}_{x}\underbrace{11...1}_{y})$ will become $(\underbrace{00...0}_{y})$, in which requires more N_y slots to identify the rest tags. So we have

$$E(N_{\underbrace{00..0}_{x}\underbrace{11..1}_{y}}) = E(N_{\underbrace{00..0}_{x}1}-1+N_y) = E(N^*_{x+1})+E(N_y)-1\,, \tag{25}$$

Denote N^*_n as the required slot to identify n tags from the sequence $(\underbrace{00...0}_{x}1)$, the probability distribution can be listed as follows

$$\begin{cases} & probability & required\ slots \\ 00......2 & 2/2^{n-1} & 1+N^*_n \\ \underbrace{a_1a_2...a_{n-1}2}_{\substack{a_i=0\ or\ 1,\ 1\le i\le n \\ \sum_{i=1}^{n-1} a_i=m,\ 1\le m\le n-2}} & C_{n-1}^m/2^{n-1} & 1+N_{\underbrace{00..0}_{l}\underbrace{11..1}_{m}2}{}_{\substack{\\ l+m=n,\ l\ge 1,\ m\le n-2}} \end{cases} \tag{26}$$

where $N_{\underbrace{00..0}_{l}\underbrace{11..1}_{m}2}$ denotes the number of slots from the sequence $\underbrace{00...0}_{l}\underbrace{11...1}_{m}2$, $l+m=n-1$, $l\ge 1$, $m\le n-2$. After reading $N^*_{l+1}-1$ slots, the reader can identify l tags, and the count sequence becomes $\underbrace{00...0}_{m}1$. According to the above analysis, the reader needs N^*_{m+1} more slots to identify the rest

$m+1$ tags. So the total number of slots from the sequence $\underbrace{00...0}_{l}\underbrace{11...1}_{m}2$ can be written as

$$N_{\underbrace{00..0}_{l}\underbrace{11..1}_{m}2} = N^*_{l+1} + N^*_{m+1} - 1\,, \tag{27}$$

Therefore, according to Eqs. (26) and (27), N_n^* can be expressed as

$$\begin{aligned} E(N_n^*) &= \tfrac{1}{2^{n-1}}\left(1+E(N_n^*)\right) + \sum_{m=1}^{n-2} \tfrac{C_{n-1}^m}{2^{n-1}}(1+ \\ &\quad E(N_{\underbrace{00..0}_{l}\underbrace{11..1}_{n-1-l}2})) + \left(\tfrac{1}{2^{n-1}}\left(1+E(N_n^*)\right)\right) \\ &= \tfrac{1}{2^{n-1}}\left(1+E(N_n^*)\right) + \sum_{m=1}^{n-2} \tfrac{C_{n-1}^m}{2^{n-1}}(E(N^*_{m+1}) \\ &\quad +E(N^*_{n-m})) \;+ \tfrac{1}{2^{n-1}}\left(1+E(N_n^*)\right)\,, \end{aligned} \tag{28}$$

Transforming the Eq. (28), we can have

$$E\left(N_n^*\right) = \frac{\frac{2}{2^{n-1}} + \sum\limits_{m=1}^{n-2} \frac{C_{n-1}^m}{2^{n-1}}\left(E\left(N^*_{m+1}\right) + E\left(N^*_{n-m}\right)\right)}{\left(1-\frac{1}{2^{n-2}}\right)}\,, \tag{29}$$

Continue to transform Eq. (29), we can further have

$$(2^{n-1}-2)E(N_n^*) = 2+\sum_{m=1}^{n-2} C_{n-1}^m\left(E(N^*_{m+1}) + E(N^*_{n-m})\right)\,, \tag{30}$$

Since $m = n-1-l$, the $\sum\limits_{m=1}^{n-2} C_{n-1}^m E(N^*_{n-m})$ can be rewritten as

$$\begin{aligned} \sum_{m=1}^{n-2} C_{n-1}^m E(N^*_{n-m}) &= \sum_{m=1}^{n-2} C_{n-1}^{n-1-m} E(N^*_{n-m}) \\ &= \sum_{l=1}^{n-2} C_{n-1}^{l} E(N^*_{l+1}) \\ &= \sum_{m=1}^{n-2} C_{n-1}^{m} E(N^*_{m+1})\,, \end{aligned} \tag{31}$$

Substitute Eq. (31) into Eq. (30), $E\left(N_n^*\right)$ can be re-expressed as

$$E(N_n^*) = \frac{1+\sum\limits_{m=1}^{n-2} C_{n-1}^m E(N^*_{m+1})}{2^{n-2}-1}\,, \tag{32}$$

According to Eq. (32), $E\left(N_n\right)$ can be computed as

$$\begin{aligned} E(N_n) &= \tfrac{1}{2^n}\left(1+E(N_n)\right) + \tfrac{1}{2^n}\left(1+E(N_n)\right) \\ &\quad + \sum_{x=1}^{n-1} \tfrac{C_n^x}{2^n}\left(1+E(N_{\underbrace{00..0}_{x}\underbrace{11..1}_{n-x}})\right) \\ &= \tfrac{2}{2^n}\left(1+E(N_n)\right) + \sum_{x=1}^{n-1} \tfrac{C_n^x}{2^n}\left(E(N^*_{x+1}) + E(N_{n-x})\right)\,, \end{aligned} \tag{33}$$

Therefore, $E\left(N_n\right)$ can be further expressed as

$$E(N_n) = \frac{\frac{2}{2^n} + \sum\limits_{x=1}^{n-1} \frac{C_n^x}{2^n}(E(N^*_{x+1}) + E(N_{n-x}))}{\frac{2^{n-1}-1}{2^{n-1}}}\,. \tag{34}$$

Finally, according to Eqs. (23) and (34), the theorem 1 can be yielded.

Appendix B
Proof of Lemma 1

We denote $B_k(k=1,2,...,n)$ as the number of groups containing k tags, $E(N_k)$ as the expected number of slots to identify k tags. For each group, the fill level of k tags is described by a binomial distribution with $1/N$ occupied probability as

$$P_k = C_n^k\left(\frac{1}{N}\right)^k\left(1-\frac{1}{N}\right)^{n-k}\,, \tag{35}$$

So the expectation of B_k can be written as

$$E\left(B_k\right) = N\cdot P_k = NC_n^k\left(\frac{1}{N}\right)^k\left(1-\frac{1}{N}\right)^{n-k}\,, \tag{36}$$

Thus, the expectation of S_n can be calculated as

$$E\left(S_n\right) = \sum_{k=0}^{n} E\left(B_k\right)\times E\left(N_k\right). \tag{37}$$

Accordingly, the system throughput of GBSA can be expressed as

$$\begin{aligned} T_{sys}^{GBSA} &= \tfrac{n}{E(S_n)} = \tfrac{n}{\sum\limits_{k=0}^{n} E(B_k)\times E(N_k)} \\ &= \tfrac{n}{\sum\limits_{k=0}^{n} N\times P_k\times E(N_k)}\,. \end{aligned} \tag{38}$$

Appendix C
Proof of Theorem 2

According to lemma 1 and Eq. (14), the system throughput of GBSA can be approximated as

$$T_{sys}^{GBSA} \approx \frac{1}{g(f)}\,, \tag{39}$$

where $g(f) = f\left[1+\sum\limits_{k=2}^{20}\frac{1}{k!}f^{-k}\left(\frac{1}{e}\right)^{\frac{1}{f}}\left(E(N_k)-1\right)\right]$. Let $g'(f)=0$, the optimal system throughput can be achieved when $f=0.7273$ because of $g''\left(0.7273\right)>0$. We can have

$$T_{sys}^{GBSA} \approx \frac{1}{g\left(0.7273\right)} \approx 0.5022\,. \tag{40}$$

Appendix D
Proof of Lemma 2

$B_k(k=1,2,...,n)$ is the number of groups containing k tags. $E(G_{R-coll})$ and $E(G_{coll})$ are the expected number of R-collision slots and ID-collision slots to identify k tags, respectively. According to the fundamental of GBSA, a R-collision slot means that tags in a slot will be split into two subsets, and we can have

$$1+2\times E\left(G_{R-coll}\right)+E\left(G_{coll}\right) = k+E\left(G_{R-coll}\right)+E\left(G_{coll}\right)\,, \tag{41}$$

Then

$$E\left(G_{R-coll}\right) = k-1\,. \tag{42}$$

So, the expected number of R-collision slots to identify n tags can be written as

$$\begin{aligned} E\left(N_{R-coll}\right) &= \sum_{k=0}^{n} E\left(B_k\right)\times(k-1) \\ &= \sum_{k=2}^{n} E\left(B_k\right)\times(k-1)\,, \end{aligned} \tag{43}$$

The Eq. (42) can be further rewritten as

$$\begin{aligned} E\left(N_{R-coll}\right) &= n + E(B_0) - N \times \sum_{k=0}^{n} P_k \\ &= n - N \times \left(1 - \left(1 - \tfrac{1}{N}\right)^n\right) \\ &\approx n \times \left[1 - f \times \left(1 - \left(\tfrac{1}{e}\right)^{\frac{1}{f}}\right)\right] \\ &\approx 0.456n\,. \end{aligned} \tag{44}$$

Appendix E
Proof of Theorem 3

Referring to the calculation in Lemma 1, we can derive the expected idle slots consumed by GBSA to identify n tags as

$$\begin{aligned} N_{idle} = N \times E\left(B_0\right) = N \times \left(1 - \tfrac{1}{N}\right)^n \\ \approx n \times f \times \left(\tfrac{1}{e}\right)^{\frac{1}{f}} \approx 0.1839n\,. \end{aligned} \tag{45}$$

According to the theorem 1 and lemma 2, the expected number of total slots and R-collision slots can be written as

$$E\left(N_{total}\right) \approx 1.9912n\,. \tag{46}$$

$$E\left(N_{R-coll}\right) \approx 0.456n\,. \tag{47}$$

Then the expected number of collision slots expended by GBSA can be expressed as

$$E\left(N_{coll}\right) \approx 0.3513n\,. \tag{48}$$

According to the definition of time efficiency Eq. (19) and Eqs. (45)-(48), theorem 3 can be given.

References

[1] F. Gandino, B. Montrucchio, M. Rebaudengo, E. Sanchez, "On improving automation by integrating RFID in the traceability management of the agri-food sector," *IEEE Trans. Ind. Electron.*, vol. 56, no. 7, pp. 2357-2365, 2009.

[2] G. M. Gaukler, "Item-level RFID in a retail supply chain with stockout-based substitution," *IEEE Trans. Ind. Informat.*, vol. 7, no. 2, pp. 362-370, 2011.

[3] C. He, Z. Wang, and C. Miao, "Block-level unitary query: enbaling orthogonal-like space-time code with query diversity for MIMO backscatter RFID," *IEEE Trans. Wireless Commun.*, vol. 15, no. 3, pp. 1937-1949, 2016.

[4] EPCglobal, EPC radio-frequency identify protocols class-1 generation-2 UHF RFID protocol for communications at 860MHz-960 MHz ver. 2. 2. 0, 2013.

[5] W.-T. Chen, "An accurate tag estimate method for improving the performance of an RFID anticollision algorithm based on dynamic frame length ALOHA," *IEEE Trans. Autom. Sci. Eng.*, vol. 6, no. 1, pp. 9-15, 2009.

[6] B. Knerr, M. Holzer, C. Angerer, and M. Rupp, "Slot-wise maximum likelihood estimation of the tag population size in FSA protocols," *IEEE Trans. Commun.*, vol. 58, no. 2, pp. 578-585, 2010.

[7] P. Solic, Z. Blazevic, M. Skiljo, L. Patrono, R. Colella, and J. P. C. Rodrigues, "Gen2 RFID as IoT enabler: characterization and performance improvement," *IEEE Wireless Commun.*, vol. 24, no. 3, pp. 33-39, 2017.

[8] J. Vales-Alnoso, V. Bueno-Delgado, E. Egea-Lopez, F. Gonzalez-Castano, and J. J. Alcaraz, "Multiframe maximum-likelihood tag estimation for RFID anticollision protocols," *IEEE Trans. Ind. Informat.*, vol. 7, no. 3, pp. 487-496, 2011.

[9] V. Bueno-Delgado and J. Vales-Alnoso, "On the optimal frame-length configuration on real passive RFID systems," *J. Network and Comput. Appl.*, vol. 34, no. 3, pp. 864-876, 2011.

[10] L. Zhu and T.-S. P. Yum, "Optimal framed aloha based anti-collision algorithms for RFID systems," *IEEE Trans. Commun.*, vol. 58, no. 12, pp. 3583-3592, 2010.

[11] L. Barletta, F. Borgonovo and M. Cesana, "A formal proof of the optimal frame setting for dynamic-frame aloha with known population size," *IEEE Trans. Inf. Theory.*, vol. 60, no. 11, pp. 7221-7230, 2014.

[12] X. Jia, Q. Feng, and C. Ma, "An efficient anti-collision protocol for RFID tag identification," *IEEE Commun. Lett.*, vol. 14, no. 11, pp. 1014-1016, 2010.

[13] H. Landaluce, A. Perallos, E. Onieva, L. Arjona, and L. Bengtsson, "An energy and identification time decreasing procedure for memoryless RFID tag anticollision protocols," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 4234-4247, 2016.

[14] J. Su, Z. Sheng, L. Xie, and G. Wen, "Idle-slots elimination based binary splitting anti-collision algorithm for RFID," *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2394-2397, 2016.

[15] L. Zhang, W. Xiang, and X. Tang, "An efficient bit-detecting protocol for continuous tag recognition in mobile RFID systems," *IEEE Trans. Mobile Comput.*, vol. 17, no. 3, pp. 503-516, 2018.

[16] J. Myung, W. Lee, J. Srivastava, and T. K. Shih, "Tag-splitting: Adaptive collision arbitration protocols for RFID tag identification," *IEEE Trans. Parallel Distrib. Syst.*, vol. 18, no. 6, pp. 763-775, 2007.

[17] Y. Cui and Y. Zhao, "Performance evaluation of a multi-branch tree algorithm in RFID," *IEEE Trans. Commun.*, vol. 58, no. 5, pp. 1356-1364, 2010.

[18] J. I. Capetanakis, "Tree algorithms for packet broadcast channels," *IEEE Trans. Inf. Theory*, vol. IT-25, pp. 505-515, 1979.

[19] B. S. Tsybakov and V. A. Mikhailov, "Random multiple access of packets: part-and-try algorithm," *Problemy Peredachi Informatsii*, vol. 16, pp. 65-79, 1980.

[20] L. Zhang, W. Xiang, X. Tang, Q. Li, and Q. Yan, "A time-and energy-aware collision tree protocol for efficient large-scale RFID tag identification," *IEEE Trans. Industrial Informat.*, vol. 14, no. 6, pp. 2406-2417, 2018.

[21] J. Su, Z. Sheng, G. Wen, and V. Leung, "A time efficient tag identification algorithm using dual prefix probe scheme (DPPS)," *IEEE Signal Process. Lett.*, vol. 23, no. 3, pp. 386-389, 2016.

[22] L. Zhang, J. Zhang, and X. Tang, "Assigned tree slotted aloha RFID tag anti-Collision protocols," *IEEE Trans. Wireless Commun.*, vol. 12, no. 11, pp. 5493-5505, 2013.

[23] T. F. L. Porta, G. Maselli, and C. Petrioli, "Anticollision protocols for single-reader RFID systems: temporal analysis and optimization," *IEEE Trans. Mobile Comput.*, vol. 10, no. 2, pp. 267-279, 2011.

[24] Y. Lai, L. Hsiao, and B. Lin, "Optimal slot assignment for binary tracking tree protocol in RFID tag identification," *IEEE/ACM Trans. Netw.*, vol. 23, no. 1, pp. 255-268, 2015.

[25] C. Qian, Y. Liu, R. H. Ngan, and L. M. Ni, "ASAP: Scalable collision arbitration for large RFID systems," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 7, pp. 1277-1288, 2013.

[26] R. G. Gallager, "Conflict resolution in random access broadcast networks," in *Proc. AFOSR workshop in Communications Theory and Applications*, 1978.

[27] Y. H. Chen, S. J. Horng, R. S. Run, et al., "A novel anti-collision algorithm in RFID systems for identifying passive tags," *IEEE Trans. Ind. Informat.*, vol. 6, no. 1, pp. 105-121, 2010.

[28] C. Angerer, R. Langwieser, and M. Rupp, "RFID reader receivers for physical layer collision recovery," *IEEE Trans. Commun.*, vol. 58, no. 12, pp. 3526-3537, 2010.

[29] J. Su, Z. Sheng, D. Hong, and V. Leung, "An efficient sub-frame based tag identification algorithm for UHF RFID systems," *Proc. 2016 IEEE Int. conf. Commun. (ICC 2016)*, Kuala Lumpur, pp. 1-6, 2016.

[30] W.-T. Chen, "Optimal frame length analysis and an efficient anticollision algorithm with early adjustment of frame length for RFID systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3342-3348, 2016.

[31] Y. Chen, J. Su, and W. Yi, "An efficient and easy-to-implement tag identification algorithm for UHF RFID systems," *IEEE Commun. Lett.*, vol. 21, no. 7, pp. 1509-1512, 2017.

[32] P. Solic, J. Radic, and N. Rozic, "Energy efficient tag estimation method for ALOHA-based RFID systems," *IEEE Sensors J.*, vol. 14, no. 10, pp. 3637-3647, 2014.

[33] P. Solic, J. Radic, and N. Rozic, "Early frame break policy for Aloha-based RFID systems," *IEEE Trans. Autom. Sci. Eng.*, vol. 13, no. 2, pp. 876-881, 2016.

[34] J.-B. Eom and T.-J. Lee, "Accurate tag estimation for dynamic framed slotted Aloha in RFID systems," *IEEE Commun. Lett.*, vol. 14, no. 1, pp. 60-60, 2010.

[35] Y. He and X. Wang, "An aloha-based anti-collision algorithm for RFID systems," *IEEE Wireless Commun.*, vol. 20, no. 5, pp. 152-158, 2013.

[36] L. Arjona, H. Landaluce, A. Perallos, and E. Onieva, "Timing-aware RFID anti-collision protocol to increase the tag identification rate," *IEEE Access*, vol. 6, pp. 33529-33541, 2018.

[37] L. Zhang, W. Xiang, and X. Tang, “An adaptive anti-collision protocol for large-scale RFID tag identification,” *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 601-604, 2014.

[38] Y. C. Lai, L. Y. Hsiao, H. Chen, C. N. Lai, and J. Lin, “A novel query tree protocol with bit tracking in RFID tag identification,” *IEEE Trans. Mobile Comput.*, vol. 12, no. 10, pp. 2063-2075, 2013.

[39] H. Wu, Y. Zeng, J. Feng, and Y. Gu, “Binary tree slotted ALOHA for passive RFID tag anticollision,” *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 1, pp. 19-31, 2013.

[40] J. Su, Z. Sheng, D. Hong, and G. Wen, “An effective frame breaking policy for dynamic framed slottted Aloha in RFID,” *IEEE Commun. Lett.*, vol. 20, no. 4, pp. 692-695, 2016.

[41] X. Liu, X. Xie, S. Wang, J. Liu, D. Yao, J. Cao, K. Li, “Efficient range queries for large-scale sensor-augmented RFID systems,” *IEEE/ACM Trans. Netw.*, vol. 27, no. 5, pp. 1873-1886, 2019.

[42] V.-H. Duong, N. X. Hieu, H.-S. Lee, and J. W. Lee, “A battery-assisted passive EPC Gen-2 RFID sensor tag IC with efficient battery power management and RF energy harvesting,” *IEEE Trans. Ind. Electron.*, vol. 63, no. 11, pp. 7112-7123, 2016.

[43] H. Guo, C. He, N. Wang, and M. Bolic, “PSR: A novel high-efficiency and easy-to-implement parallel algorithm for anticollision in RFID systems,” *IEEE Trans. Ind. Informat.*, vol. 12, no. 3, pp. 1134-1145, 2016.

[44] J. D. Griffin and G. D. Durgin, “Gains for RF tags using multiple antennas,” *IEEE Trans. Antennas. Propag.*, vol. 56, no. 2, pp. 563-570, 2008.

[45] H. Wu and Y. Zeng, “Passive RFID tag anti-collision algorithm for capture effect,” *IEEE Sensors J.*, vol. 15, no. 1, pp. 218-226, 2014.

[46] B. Li and J. Y. Wang, “Efficient anti-collision algorithm utilizing the capture effect,” *IEEE Commun.Lett.*, vol. 15, no. 3, pp. 352-354, 2011.

[47] P. Nikitin, K. Rao, R. Martinez, and S. Lam, “Sensitivity and impedance measurements of UHF RFID chips,” *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 5, pp. 1297-1302, 2009.

[48] P. Solic, J. Maras, J. Radic, and Z. Blazevic, “Comparing theoretical and experimental results in Gen2 RFID throughput,” *IEEE Trans. Autom. Sci. Eng.*, vol. 14, no. 1, pp. 349-357, 2017.

Jian Su has been a lecturer in the School of Computer and Software at the Nanjing University of Information Science and Technology since 2017. He received his PhD with distinction in communication and information systems at University of Electronic Science and Technology of China in 2016. He holds a B.S. in Electronic and information engineering from Hankou university and an M.S. in electronic circuit and system from Central China Normal University. His current research interests cover Internet of Things, RFID, and Wireless sensors networking.

Zhengguo Sheng has been a lecturer in the Department of Engineering and Design at the University of Sussex since 2015. He received his Ph.D. and M.S. with distinction at Imperial College London in 2011 and 2007, respectively, and his B.Sc. from the University of Electronic Science and Technology of China (UESTC) in 2006. His current research interests cover the Internet of Things (IoT), connected vehicles, and cloud/ edge computing.

Alex X. Liu received his Ph.D. degree in Computer Science from The University of Texas at Austin in 2006, and is a professor at the Department of Computer Science and Engineering, Michigan State University. He received the IEEE & IFIP William C. Carter Award in 2004, a National Science Foundation CAREER award in 2009, and the Michigan State University Withrow Distinguished Scholar Award in 2011. He has served as an Editor for IEEE/ACM Transactions on Networking, and he is currently an Associate Editor for IEEE Transactions on Dependable and Secure Computing and IEEE Transactions on Mobile Computing, and an Area Editor for Computer Communications. He has served as the TPC Co-Chair for ICNP 2014 and IFIP Networking 2019. He received Best Paper Awards from ICNP-2012, SRDS-2012, and LISA-2010. His research interests focus on networking and security. He is a Fellow of the IEEE.

Yu Han received the B.S. degree from University of Electronic Science and Technology of China (UESTC), Chendu, China , in 2013, where he is currently pursing the Ph.D degree. His current research focuses on Energy Harvesting Wireless Sensor Networks and Backscatter Communication.

Yongrui Chen has been an associate professor in the Department of Electronic, Electrical and Communication Engineering at the University of Chinese Academy of Sciences (UCAS) since 2014. He received his Ph.D. at UCAS in 2011, his M.S. at Tsinghua University in 2007, and his B.Sc. from Yanshan University in 2001. His current research interests cover the Internet of Things (IoT) and heterogeneous wireless networks.